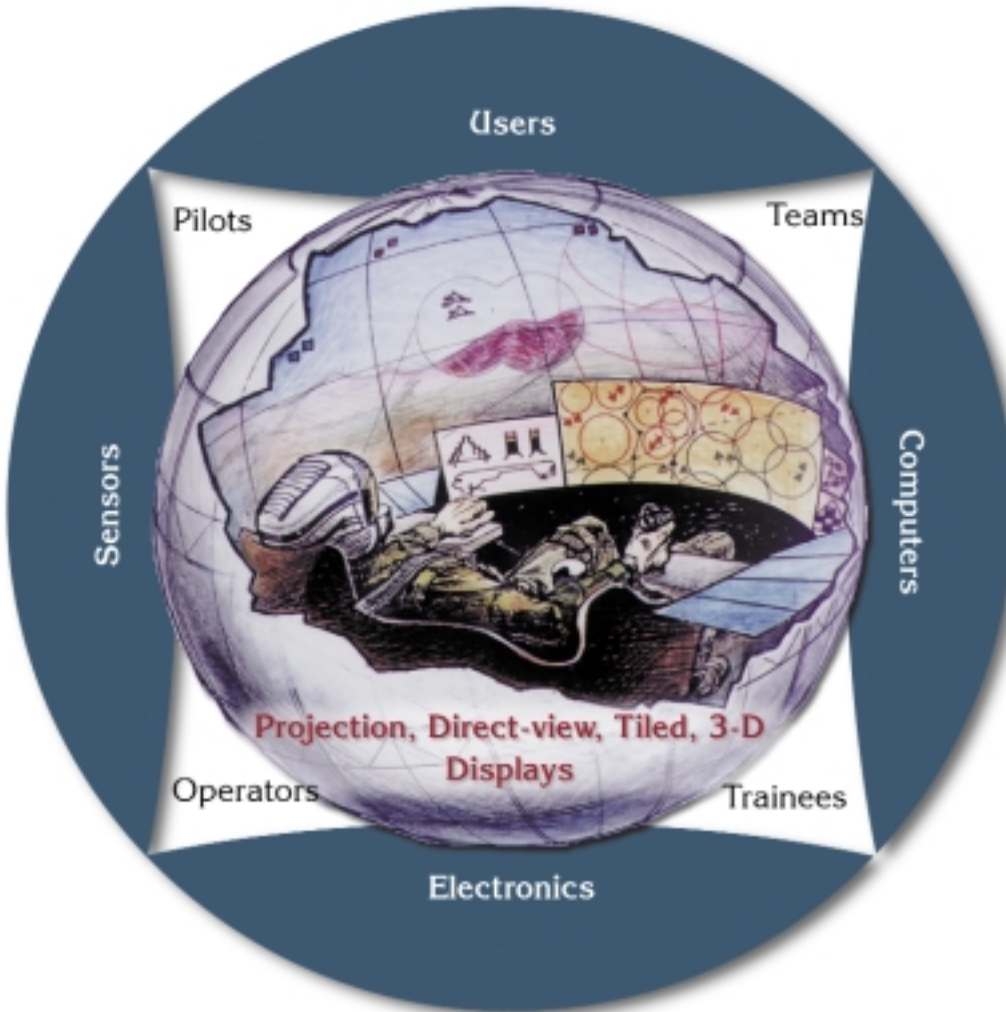**Figure 1. Gigapixel crewstation for information-centric warfare**

Display Technology Overview

Darrel G. Hopper

Warfighters require displays in all crew-stations and platforms—air, land, sea, and space. This cross-cutting need is documented in a comprehensive study of military displays in some 350 defense systems (Desjardins & Hopper, 1999). Remarkable progress over paper and mechanical visual display media has been made since the invention of the first electro-mechanical and electronic displays just a few decades ago—but far, far more remains to be done (Hopper, 2000a). Fielded displays are just peep-holes in an information universe. Warfighter productivity growth hinges on the invention and transition of more capable displays, especially those with far higher resolution. For example, the B–2 program requires the addition of a 14-inch display between the pilots, as the current 8-inch displays are not large enough to present all the threat sym-bology on a single display surface.

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This newsletter contains information on adavances in avionics Head-down displays, head-up and helmet mounted displays, decision support displays for military commands, and display technology overview. The newsletter also contains a calendar of upcoming, human systems events.

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Advanced cockpits and crewstations require panoramic display systems of over 300 inch^2 per warfighter with pixel densities increased from the current minimal 80 pixels per inch to over 200 pixels per inch to show advanced 25-megapixel sensor imagery and integrated situation awareness formats like pathway in the sky (Snow et al., 1999). Simulators require synthetic vision systems of 160 megapixels; the state-of-the-art is 16 megapixels based on 2-megapixel devices. Soldiers require both large (1 m, 30 megapixel) electronic maps and small (24 mm, 5 megapixel), low power displays yet with color and high information content. Naval surface combat information centers require 10-megapixel team knowledge walls and a true three-dimensional display system to reduce crew sizes and ensure rapid understanding of the altitude as well as the radial position of ingressing aircraft (Hopper, 2000b). The defense information-centric display challenge is illustrated in Figure 1 (see cover).

Display technology is driven by electronics, sensors, computers, and users. Electronics deals with the challenges of fabricating display devices and systems per se. Sensors provide video, still imagery, and data. Computers generate graphics and imagery from databases, sensors, and communications. Users are decision-makers consuming and acting on images of information.

This special issue provides an overview on display technology along with articles in three areas where improved visual displays are poised to revolutionize warfighter productivity:

- panoramic head-down instrument panels;
- head-up and head-mounted systems; and
- command decision suites equipped with knowledge walls and smart desks.

Displays in three other such areas—uninhabited combat air vehicle crewstations, simulators and virtual reality, and air-to-air cueing—are illustrated in recent issues of *Gateway* (Barbato, 2000; Knott, 2000; Rastikis, 1998).

Acquisition Platform Category

Display technology confronts the five Services with common challenges and opportunities. Annual defense display research appropriations total about $100 million and Congress wants a defense-wide strategy for display acquisition to guide this investment.

Display acquisition occurs by platform categories:

- aviation and space electronics (avionics),
- land vehicle electronics (vetronics),
- shipboard non-propulsive electronics (naval sea),
- mobile personnel, and
- command and control centers (C4ISR).

Avionics cockpit displays comprise some 19% of displays in fielded Department of Defense weapons systems. All certified aerospace cockpit displays—military, civil, general, and space—are custom designed; most are currently manufactured at opportunity cost in high-volume facilities in Korea, Japan, and Taiwan. The remaining 81% of fielded displays are ruggedized versions of displays designed for a non-defense market. Across all acquisition programs the cost of a fielded display comprises just 10% for the device per se and some 90% for packaging and testing to meet military performance specifications. Thus, from a cost perspective all combat displays are custom.

Aviation acquisition has been a key driver of display research for 100 years. Display research for aircraft crewstations began with mechanical and electromechanical (EM) instrumentation about 1900. Avionics display research was undertaken beginning with the cathode ray tube (CRT) in the 1930s through the 1980s. Flat-panel display (FPD) research began at the Avionics Laboratory (now part of the U.S. Air Force Research Laboratory, AFRL) about 1969 and matured about 1992 when the active matrix liquid crystal display (AMLCD) technology became preferred over CRTs for all military and civil aerospace cockpits. New FPDs cost 25% as much but are over 30 times more reliable than the old CRT and EM technologies they replace. Now AMLCDs are better than CRTs in virtually every performance parameter, including angle of view. The 1903 Wright Flyer had three instruments (mechanical displays): wind gauge, propeller RPM counter, and stop watch. The year 2001 F–22A Raptor has six multifunction AMLCDs totaling 1.2 megapixels in 201 inch^2 (49% of the instrument panel).

Mission C4ISR crew workstations in air, sea, and land systems typically provide each operator a 19-inch color display with 1.3 megapixel resolution. The U.S. Air Force recently switched the design of these 19-inch displays from direct-view CRTs to

projectors using digital micromirror devices (DMD). The DMD technology was developed in a DARPA-funded, AFRL-managed exploratory research project from 1991–1995 and transitioned via the Common Large Area Display Set (CLADS) logistics project at Warner-Robins ALC from 1996–1999. Army and Navy programs have recently adopted DMD workstations as well.

Command and control centers are moving to 10-megapixel anchor desks and workbenches and 100-megapixel knowledge walls and information igloos (pixelated rooms) to enable ten persons to make better decisions in combat than by 30 persons at present. Display tiling technology from commercial trading floors, broadcaster studios, and advertising, enabled by prior defense research, is now fueling a revolution in military decision-making suites.

Design Class

Display designs are classified as direct-view, projection-view, tiled, and true three-dimensional. The viewer is usually presented with an image via a physical screen. Direct-view displays create the image in the plane of the screen via large electro-optic devices. Projection-view displays use miniature electro-optic devices together with an optics system that magnifies the image some 10 to 1000 times while transmitting it to the screen. Tiled displays create an image having higher luminance, resolution and size from multiple, individually less capable, modules. True three-dimensional designs provide multiperspective images, not just three-dimensional models depicted on two-dimensional hardware (Hopper, 2000b).

Mass production displays are typically just 0.8 megapixel for both direct- and projection-view designs. Niche and exotic market production for tiled systems are typically just 5–16 megapixels. The highest resolution direct-view display is the 22-inch, 9.2-megapixel color AMLCD announced by IBM in September 2000; twelve of these devices are being used to create a 114 megapixel datawall for computational research in the Department of Energy. Projection displays up to 5 megapixels are becoming available based on miniature AMLCDs. The biggest jumbo tiled display is the unique $37 million NASDAQ Times Square cylindrical building facade display: 2.1 megapixels, with nine subpixels per color pixel, comprising over 18 million inorganic light emitting diodes (ILED) and covering 1000 m^2 (10,800 feet^2).

Size, Pixel Density, Resolution

Size for displays relates to image, device, and screen. Individual display screens produce an image that subtends an instantaneous field-of-view of about 0.01 to 2 steradians (sr) (5 x 5° to 100 x 100°) at the design eye point; tiled systems go up to the maximum of 4π, or 12.566 sr. Thus, a 40 x 40° (0.24 sr) display image is just 2% of the 4π sr natural world. Usable AMLCDs for image presentation appeared in production about 1988 when pixel size decreased below 317 mm with screen size about 3 inches and resolution of 0.0324 megapixels; the image size was 2.25 x 2.25 inches, or about 5 x 5° (0.01 sr) at 24 inches. From 1988 to 2000, direct-view AMLCD device size has increased from 3 to 30 inches and resolution has increased from 0.03 to 9 megapixels. Device pixel densities in 1988 were 80 per inch; now the pixel density is up to 120 per inch in products and 211 per inch in prototypes.

Technology Pace and Variants

Displays operate by reflection, transmission, or emission of light from the imaging device and screen. There was only one electronic display technology in 1940: the CRT. Circa 2000 there are two dominant display technologies: CRT and flat-panel AMLCD. Technology creation, transfer, and transition have become significantly more productive with each new economically viable generation of electronic displays. The CRT technology took some 52 years from invention in 1896 to mass market television beginning in about 1947. The AMLCD technology took some 23 years from the first research funding about 1969 until it was fielded on aircraft and supported the launch of the notebook computer industry by about 1992. The DMD technology took just six years from first research to commercial presentation projector launch and nine years to the first military production contract.

Two new technologies, reflective AMLCD on silicon substrate (LCOS) and the active matrix organic light-emitting diode (AMOLED), appear to be moving towards successful commercialization and operational military use as fast as did the DMD. Some older technologies have established niche markets: alternating current gas plasma (ACGP), vacuum fluorescent display (VFD), thin film and active matrix electroluminescent (TFEL, AMEL), and liquid crystal shutter three-dimensional

Table 1. Electronic display comparisons

Design Class	Device Size (diagonal in mm)	Market*	Technologies	
			Emissive	**Light Valve**
Direct-view	Large: 25 to 1,000	Mass Niche Future	CRT ACGP, VFD, TFEL, OLED FED, FSD	AMLCD, EM EMS
Projection-view	Micro: 3 to 24	Niche Future (device): Future (direct write): Future (waveguide screens):	CRT, AMEL AMOLED SSL, VRD PSM	AMLCD, DMD LCOS, GLV POD, TWS
Tiled	Jumbo: 3,000 to 30,000	Niche-mass Exotic Future	Incandescent, neon ILED, CRT FED, OLED	Macroscopic shutters GDL, AMLCD
True 3–D	Various	Niche Future	Multiplexed 2–D Volumetric	Multiplexed 2–D Holographic

* Market (CY2000 unit sales):
 Mass (0.1–10+ million); Niche (1–10 thousand); Exotic (1–100); Future (August, zero)

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with glasses (stereoscopic) and without (autostereoscopic).

Future technologies—those yet to be successfully commercialized—include the flexible substrate display (FSD), solid state laser (SSL), polyplanar optic display (POD), tapered wedge screen (TWS), electrostatic microshutter (EMS), grading light valve (GLV), virtual retinal display (VRD), field emission display (FED), polymer switched matrix (PSM), gas/dye laser (GDL), and improved true three-dimensional devices (True 3–D).

Table 1 compares electronic displays by design, size, market, and technology. The following three articles will investigate many of the technologies compared in this table. ■

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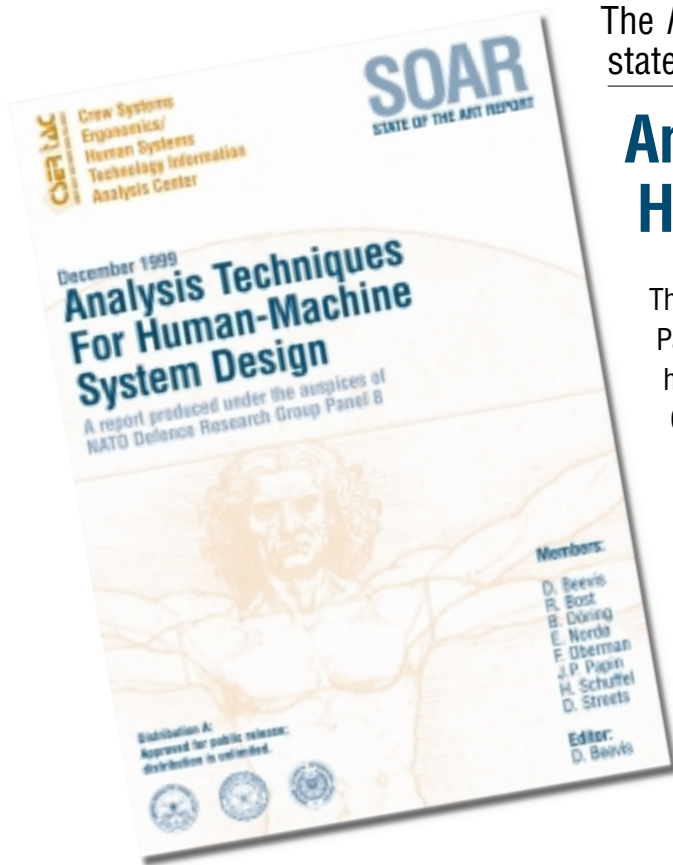
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Advances in Avionics
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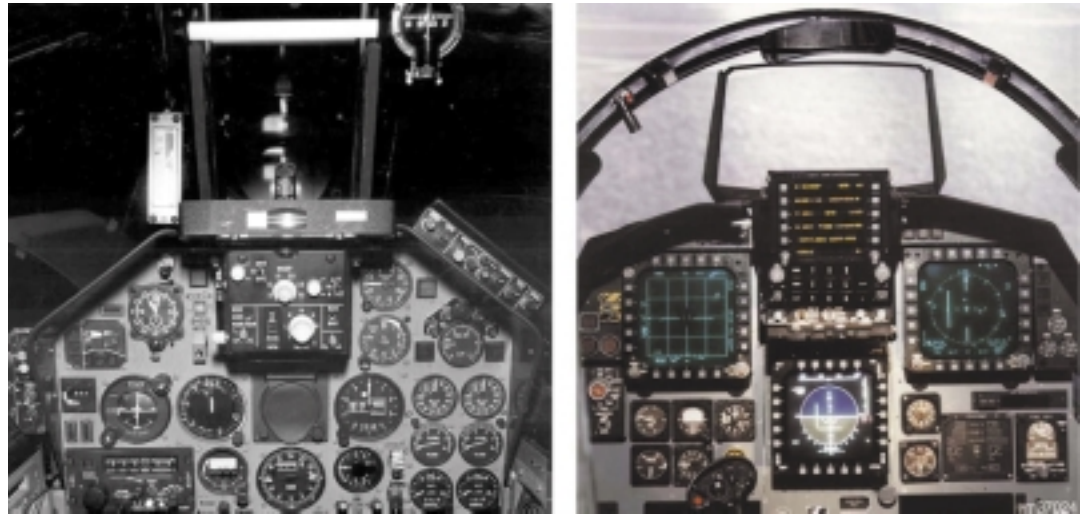
Michael H. Kalmanash

Figure 1. Electronic displays streamline cockpit instrumentation

Head-down multifunction displays (MFDs) mounted in the instrument panel are a primary means by which the modern aircraft communicates with the pilot. As shown in Figure 1, electronic MFDs, capable of providing video, graphics, and text images can replace entire clusters of dedicated instruments and can clearly present sensor video or ground maps, as well as navigation, aircraft systems status, and tactical information. In aerospace electronics, where access to information must be quick and accurate, a picture is worth more than a thousand words (or numbers).

The first avionics MFDs appeared in the early 1960s, using ruggedized television-type cathode ray tubes (CRTs) as the display medium. These early MFDs were characterized by durability (good), ambient viewability (good), viewing area (limited), bulk and weight (high), color (green) and reliability (good but not great). Despite their shortcomings, they were widely adapted, because of their clear superiority over fixed gauges and also because they could be tailored to fit the needs of a variety of different aircraft.

Like dinosaurs, however, their adaptability had limits. As aircraft cockpits became more sophisticated, increases in the information volume led to the need for better display performance (full-color, larger viewing area, higher resolution, enhanced contrast and brightness, etc.). Improved CRTs could meet only some of these needs, and even then often at the expense of unacceptable increases in weight, bulk, and power dissipation. As a result, the industry began to look for alternative (flat panel) display media for future MFDs. Flat panel display systems may be designed for either direct-view (large flat panels) or projection-view (flat panel microdisplays)—both design approaches enable significant reductions in weight, bulk, and power dissipation relative to CRT devices while simultaneously providing dramatically superior performance.

Flat Panels: The Next Generation

Despite their ability to fill niches in the commercial marketplace, some flat panel technologies, such as electroluminescent or plasma display panels, simply cannot provide adequate performance for avionics applications, while newer technologies such as field-emission displays or organic

light-emitting displays remain years away from fruition. On the other hand, active matrix liquid crystal displays (AMLCDs), the technology used in notebook computers, are capable of high resolution, full color, and most of the performance needed for avionics use, particularly when combined with special wide-range backlights designed for day and nighttime use.

Beginning in the early 1990s, as AMLCDs began their ascendancy in the commercial marketplace, several suppliers announced their intention to develop custom AMLCDs for avionics and other specialty markets. Coupled with the need for improved performance, this led to a rush to incorporate AMLCD-based MFDs into new cockpit designs. The days of the CRT were over. AMLCDs were touted by some as the ultimate avionics display medium.

This may have been a bit of an overstatement. The commercial success of direct-view AMLCDs has been based on enormous investments and high-volume manufacturing of standard products. These factors are not shared by U.S. manufacturers of custom panels who, facing high costs and poor yields, have proven unable to sustain themselves in business. Reductions in the domestic U.S. direct-view AMLCD supplier base have led to skyrocketing costs and even delayed completion of new aircraft.

As a result, the avionics community has faced pressure to try to design cockpits around standard commercial AMLCDs or to purchase capacity for custom runs at Asian commercial fabrication facilities. In many instances adapting to commerical standards is simply not possible. A key issue is size. Most commercial displays are rectangular, while aircraft installations typically require square displays (with unforgiving dimensional constraints). Additional issues such as environmental compatibility and viewing angle often mandate the use of custom or semi-custom AMLCDs as well.

Fixing the Supplier Problem

In an effort to address size/form factor issues, several groups have been investigating the "re-shaping" of commercial flat panels, whereby standard AMLCDs are cut down to fit into specific cockpit installations, following which needed

ruggedization can be accomplished. This approach shows promise, although not all dimensional requirements can be satisfied, and there are limitations to the performance that can be attained.

Another promising approach is a new class of avionics MFDs based on rear-projection technology. The core of a projection MFD is the "image engine," containing high-resolution microdisplays and color management optics. The engine is illuminated by a high-efficiency arc lamp, and its output is coupled to a high-contrast screen via projection optics. Unlike direct view displays, a common image engine and illumination system can be used in multiple applications regardless of screen size or form factor, using the projection optics to scale the image to fit the screen. This enables the use of identical commercial-off-the-shelf (COTS) components and subassemblies for multiple programs, resulting in reduced costs and shorter development cycles.

Avionics Projection MFDs

Projection technology has been under development at Kaiser Electronics since 1996, resulting in a number of prototypes ranging in size from 6 x 6 inches to 8 x 20 inches, all using similar components, as illustrated in Figure 2.

Projection displays are currently under development for the Primary

Figure 2. One size fits all: Projection MFDs use common components

Figure 3. Projection MFDs in the F–22 and F/A–18E/F

For more information, please contact:

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Multifunction Display (PMFD) for the F–22 aircraft as well as the Digital Expandable Color Display (DECD) for the F/A–18E/F, as illustrated in Figure 3. Despite their size differences (the PMFD has an 8 x 8 inch screen while the DECD is 6 x 6 inches), both of these units incorporate common core sub-assemblies, which significantly reduces costs for both programs. Additionally, Lockheed-Martin has selected Kaiser projection technology for the Joint Strike Fighter aircraft, and prototype units have been delivered to Lockheed for evaluation and demonstration.

Summary

Spiraling costs and supplier uncertainty have raised concerns about the future viability of direct view AMLCDs for avionics applications. Rear projection display technology based on COTS components is emerging as an attractive alternative, offering cross-platform commonality, lower costs, and multi-source availability of key components. Using this approach, the potential exists for what may well be the ultimate avionics display, the reconfigurable panoramic cockpit system shown in Figure 4.■

Figure 4. Projection technology enables the "ultimate" cockpit display

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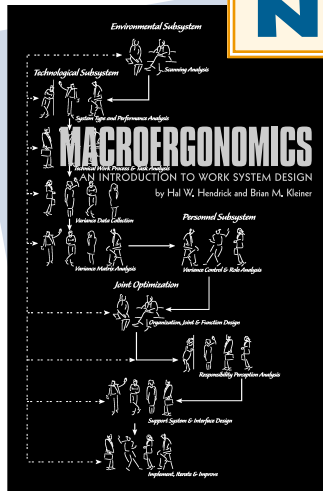
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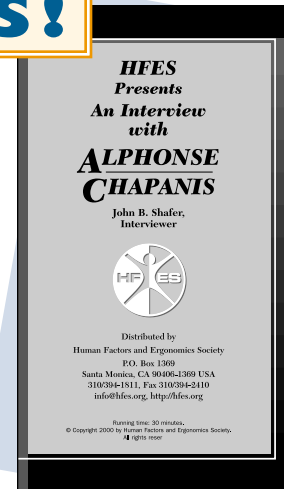
Human Factors Pioneer Alphonse Chapanis

HFES announces a new video featuring an interview with human factors/ergonomics pioneer Alphonse Chapanis. In addition to a broad-ranging discussion of Chapanis's work and interests, the video contains photos and illustrations from Chapanis's own collection. Topics include his contribution to the Johns Hopkins Systems Research Project, which led to publication of the text *Applied Experimental Psychology,* his work on the "touch-tone" configuration on Bell Labs telephones, and his teaching and consulting experiences. The video was produced by interviewer John Shafer. VHS, 30 min. $30 for HFES members, $40 for nonmembers. Add $7 for US shipping, $10 non-US.

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Head-Up and
Helmet-Mounted Displays

C. T. Bartlett and
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The head-up display (HUD) has been a vital information medium in the military cockpit since the first installation in the United Kingdom Royal Navy Buccaneer in 1961. In more recent years some HUD installations have become classified as primary flight instruments.

The helmet-mounted display (HMD) has a long development history with early versions already fielded by several countries, including Russia and Israel (Adam, 1997; Bartlett, 2000; Rastikis, 1998). Only recently have HMD production programs begun to emerge in the US and UK. The initial installation has often been in the form of a sight where the capability to launch off-boresight weapons was added to the existing capability of the HUD as a weapon release system. The more complex HMDs offer the display capability of a HUD with the advantage of being able to see that display within a large range of head motion.

Head-Up Displays

The HUD has been proven over many years to be a means of providing vital flight, navigation, aircraft data, and weapon release parameters. The earliest gunsights provided little more functionality than an aiming system for the guns, but with the introduction of increasingly sophisticated computational capability, complex manual air-to-air and air-to-ground weapon release became possible with enhanced accuracy. Now the HUD usually forms part of an integrated weapon aiming and release system where automatic modes of release are programmed in for the different weapon stores and release conditions.

In recent years it has been possible to introduce sensor video from forward-looking infrared (FLIR) video-imaging sensor onto the HUD such that operation by night can be achieved with much the same capability as daytime operation. The HUD can provide cursively drawn symbology in a high luminance mode for day operation, and it also can draw the same suite of symbology over the raster video scene at night at a much lower luminance.

The HUD's field of view was not initially an important issue when the HUD was used solely as a sight, because the guns were rigidly fixed to the airframe and the whole aircraft was turned towards the target. A 20˚ total field of view is entirely adequate for this role. However a large field of view is highly desirable to reduce the workload of a pilot using the HUD to fly at low level, to provide "look into turns" and to compensate for changes in angle of attack caused by variations in weight, stores, or speed. By day at low level flight the peripheral cues of surrounding terrain received by the pilot are an important feature, but at night these cues are missing.

In the latest generation of fast jets such as Eurofighter and Grippen, the field of view of the HUD is designed to be as large as possible. The HUD in these aircraft is a primary flight instrument and a HMD is either not fitted, used, or no more than a missile release site.

BAE SYSTEMS has developed an operational military HUD for the Eurofighter 2000 (see Figure 1). This has a single element "diffractive" combiner using new computer-generated holographic techniques to take out the distortion. The combiner is flat, which minimizes real-world distortion and has a field of view of 30˚ x 25˚. This design is capable of cursive, raster, and hybrid operation, and is sunlight readable. The minimal support structure for the combiner optic is minimized in size to give pilots optimum visibility for air-to-air combat while maintaining a highly rigid mount. The two-seat variant of the Eurofighter has a similar HUD in the rear seat that can display video from the forward HUD camera (see Figure 2). This design is based on current component technologies. A key design feature is system integrity: the HUD is so reliable that the pilot no longer needs to monitor the HUD against other

Figure 1. The Eurofighter head-up display

instruments, thus reducing workload for the single-seat Eurofighter 2000 compared to the Tornado, for example. Such a HUD is a true primary flight instrument in that it does not need to be compared against the standard instruments to ensure integrity. An earlier implementation of a HUD as a primary (i.e., high-integrity) flight instrumentation system is now operational on the BAE SYSTEMS HUD fitted to the C–17 transport (see Figure 3). The C–17 HUD was designed by BAE SYSTEMS for Lockheed-Martin in the US and introduced high integrity via the avionics concept of dual dissimilar processors with backward path monitoring, a concept pioneered in digital avionic flight control systems.

Helmet-Mounted Displays

The major drawback of a HUD is that the display is in a fixed forward position and it is always necessary to turn the aircraft to bring the display over the target. A large field of view for the HUD improves this, but it is still a very small proportion of the pilot's potential head movement and the best HUD field of view is still inadequate to encompass the off-boresight launch angle of modern missiles.

The solution is to put the display on the pilot's head so that the image is always located where he is looking. This concept is the helmet-mounted display, by which the appropriate data can be displayed accurately aligned to the real world in virtually whichever direction the pilot is looking. A HMD may not resolve the issue of peripheral cues, but the ability to scan the environment is a big improvement.

The use of a helmet-mounted system for sighting is well established and BAE SYSTEMS has such a system on the Royal Air Force Jaguar (shown in Figure 4). The application to a full day and night capability has taken longer and initial usage has been on helicopters such as the German Tiger (shown in Figure 5). The BAE SYSTEMS Striker helmet shown in Figure 6 has been designed for flexibility; can be mounted, depending upon the mission (day, night); and has an open systems architecture design that enables future capabilities to be readily added when research permits (e.g., audio integrated into the day/night visual systems). The basic system provides a 40° fully overlapped binocular display with a high
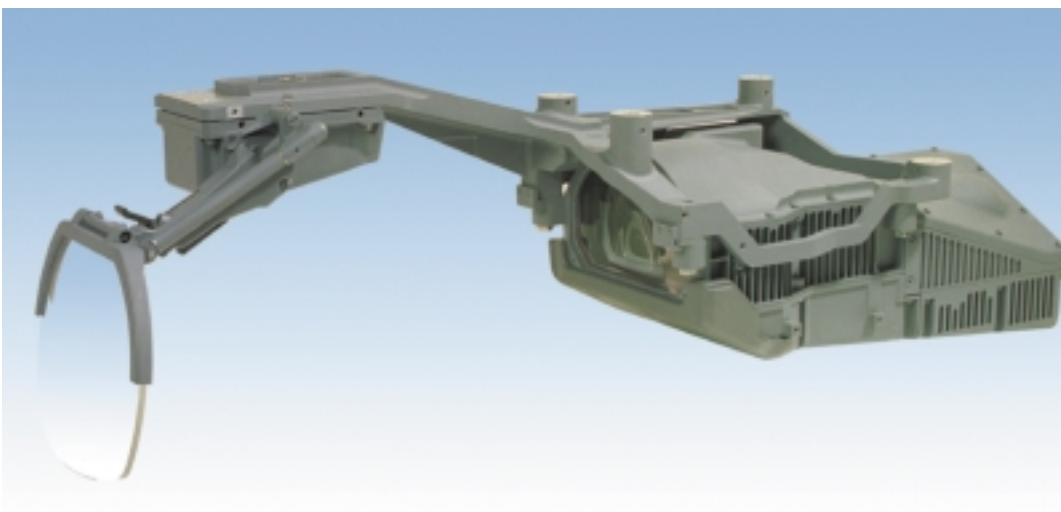
Figure 2. Two-seat variant of the Eurofighter for the rear seat

Figure 3. The C–17 head-up display

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Figure 4. The Jaguar helmet-mounted sight

Figure 5. The helmet-mounted display for the German Tiger helicopter

luminance cursive mode and video mode with symbology overlay.

There is a clear distinction here between HMD and helmet-mounted sighting systems. Sighting systems allow high off-boresight weapons aiming and employment. Displays, on the other hand, include flight parameters, such as height, heading, altitude, and airspeed, as well as being able to display video imagery from FLIR or night-vision sensors. This is one of the most important tactical advances technology has offered the fighter pilot. For example it allows the pilot to remain visually focused on the target without having to go "heads in" to check altitude for a high-to-low conversion. Having target designator (TD) boxes no longer confined to the field of view of the HUD is another huge benefit of HMD's. However care has to be taken not to visually overload the pilot or obscure the view of the outside world.

What About the Future?

There is a growing need to provide the pilot with critical tactical information while maintaining his visual and cognitive workload within known limitations. Retrofit of such displays is constrained by existing cockpit geometry and although new aircraft offer more flexibility in the cockpit layout, the HMD offers the best solution. It is foreseen that there will be a growing need for a helmet-mounted audio-visual system because information needs to be presented in a form that allows rapid assimilation and minimizes workload. Flight tests and laboratory experience show that visual and audio presentation should be synergistic, if correctly integrated. For example, active noise reduction (ANR) is of real benefit in high cockpit noise levels as it supplements passive techniques and reduces crew fatigue. ANR therefore creates an environment where aural senses can be used to advantage permitting two- and three-dimensional sound cues to be presented to augment visual information transfer.

If the HMD is to be used as a tactical information display it will need a larger field of view, a binocular presentation and possibly a color display. The extra cost of enhancements such as color has to provide a demonstrable performance advantage. Such an HMD may also be a cost-effective solution for operating in a high-threat (e.g., agile laser) environment by providing a "virtual reality" capability.

Other technologies may be integrated such as a non-CRT display, 3D visuals, 3D audio, ANR, and integrated NBC protection. Head-borne weight must be reduced and the performance of the helmet tracker enhanced, providing an unlimited head motion box and a lag-free output. This capability must be achieved within a small volume and at low cost within the weight and center of gravity constraints of producing a safe helmet.

Figure 6. The "Striker" helmet-mounted display

The military HUD has probably reached the limit of its development. The size and weight of the optical system and parallel costs really preclude any significant increase in field of view. There are still important areas of application. HUD's will increasingly be installed in transport aircraft where, as safety critical instruments, the integrity of these HUDs will be paramount because they have become primary flight instruments (i.e., safety critical certification is required).

The major area of improvement to both HUD and particularly HMD will be the introduction of flat panel displays (FPD). This change will eliminate the unreliable high-voltage power supply and the costly analogue drive circuits. The CRT is not particularly unreliable, but it is bulky and uses considerable power. The FPD permits the introduction of color, but there are human factors issues of the acceptability of a "pixellated" display to be resolved and the long-term commercial availability is a pressing issue.
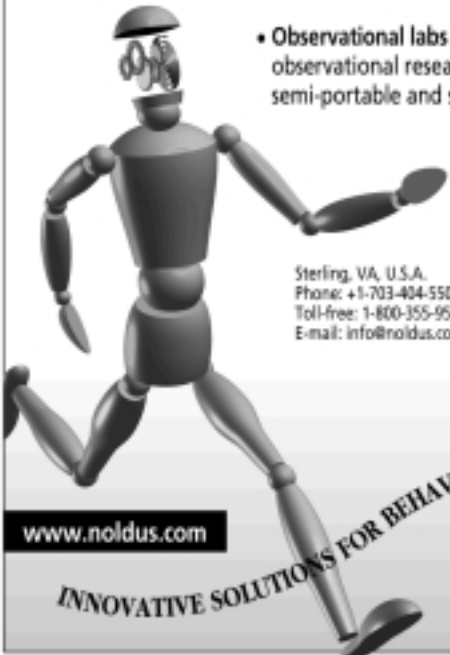
In the military field HMDs are beginning to appear in both helicopters and fast jets, but until they can offer the same accuracy and integrity as the HUD, it seems the HUD will remain for some years as a high-accuracy on-boresight display. ■

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Decision Support Displays for Military Command Centers:
Enabling Knowledge-Centric Warfare for Fleet Decision-Makers

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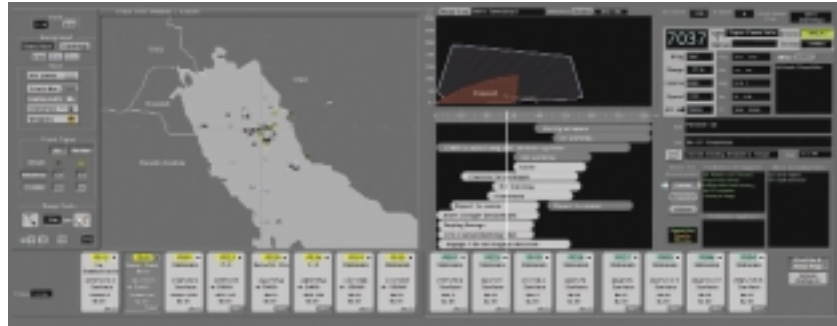
Figure 1. The TADMUS Decision Support System

The Space and Naval Warfare Systems Center–San Diego (SSC–SD), with sponsorship from the Office of Naval Research (ONR), has been striving to develop improved displays based on decision support technology for military decision-making for over ten years. At the center of this effort has been the Tactical Decision-Making Under Stress (TADMUS) project and its successors. The TADMUS project was spawned by the 1988 USS Vincennes incident where an Aegis cruiser, engaged in a littoral warfare peacekeeping mission shot down an Iranian Airbus after mistaking it for a tactical threat. Investigations following the incident suggested that stress may have affected decision-making and that these effects were not well understood. The TADMUS project was established to address these concerns.

The TADMUS project developed a series of prototype decision-support tools that ultimately came to be embodied as the integrated Decision Support System (DSS), illustrated in Figure 1. The DSS research showed that when tactical decision makers had the prototype DSS available, significantly fewer communications were needed to clarify the tactical situation, significantly more critical contacts were identified earlier, and a significantly greater number of defensive actions were taken against imminent threats. Furthermore, false alarms were reduced by 44% and correct detection of threat tracks increased by 22%. These findings suggest that the prototype DSS enhanced the commanders' awareness of the tactical situation, which in turn contributed to greater confidence, lower workload, reduced errors in adherence to rules of engagement, and more effective performance.

The Chief of Naval Operations' Strategic Studies Group XVI report *Command 21—Speed of Command* recognized the significance of the TADMUS work and that its results were more broadly applicable. They concluded that:

- Fleet decision makers are faced with too much data and not enough information.
- Fleet information systems are often not designed to support the decision makers.
- Reduced manning requirements, complex mission requirements, etc. will further exacerbate the problem.

One of the key recommendations to come out of the Command 21 report was that decision support technology developed under the TADMUS project should be extended from single-ship combatants to higher echelons of command. The Command 21 Decision Support for Operational Command Centers (Command 21) project is addressing this recommendation by conducting research into the unique requirements of decision-making within military operational command centers.

The initial Command 21 work with both the Second and Third Fleet command ships has suggested that (1) collaboration is problematic in these command centers, and (2) commercial off-the-shelf (COTS) collaboration tools often are not as useful as might be expected. Military decision makers were found to engage in "asynchronous collaboration" where each was working on different parts of a common problem in their own space and time, and as a result, each having their own decision cycle. This situation is different from traditional "synchronous" collaboration such as "brain storming." Staff-wide synchronization is largely achieved when staff briefings are given to the entire staff at watch-turnover. A central premise for Command 21 is that "speed of command" can only be achieved when it is not necessary to stop and prepare briefings so that command decision makers can be informed. The Command 21 project has developed a concept of operations for sharing information that incorporates unique, web-enabled collaboration "push" tools to provide all decision-makers ready access to the best data available at all times.

One Command 21 tool is the "knowledge wall" illustrated in Figure 2. The wall features a series of windows incorporating decision-support tools tailored to the Commander Joint Task Force (CJTF), as well as windows with "summary status" information being "pushed" from the anchor desks used by liaison officers (LNOs) representing the various CJTF departments. The battle watch captain in charge of the command center can choose which aspects of the situation to focus on, and move relevant content to the large panels in the center of the wall.

A watch-station being developed for DD–21 as part of the ONR Manning-Affordability Advanced Technology Demonstration can be adapted to allow LNO collaboration. This watch-station uses software tools (COTS and information-push web applications) together with computer display hardware as a "knowledge desk" that enables the operator to create and publish value-added information to the web. A conceptual operator console, known as a "knowledge desk," is illustrated in Figure 3 and consists of an integrated "desktop" spread across four different display surfaces. The top right LNO operator display has been dedicated to routine office tasks such as preparing briefs, processing E-mail, writing memos, etc. The top center display is dedicated to providing the tactical situation "big picture" tailored to the user's decision-making needs. The bottom center display is a dedicated place for monitoring the execution of an operational plan. The top left display is a tool explicitly designed to facilitate sharing information. The concept uses templates to "push" information from the operator to a web site viewable by the rest of the command staff. The information "pushed" consists of work sheets, forms, and prompts to others on the command staff that would facilitate their understanding information relevant to their decision-making tasks. The software tools cause the information pushed to be formatted in a manner that others would recognize and understand, and published to a shared database in the web environment.

The development of the knowledge wall was greatly accelerated through its use as part of the Global 2000
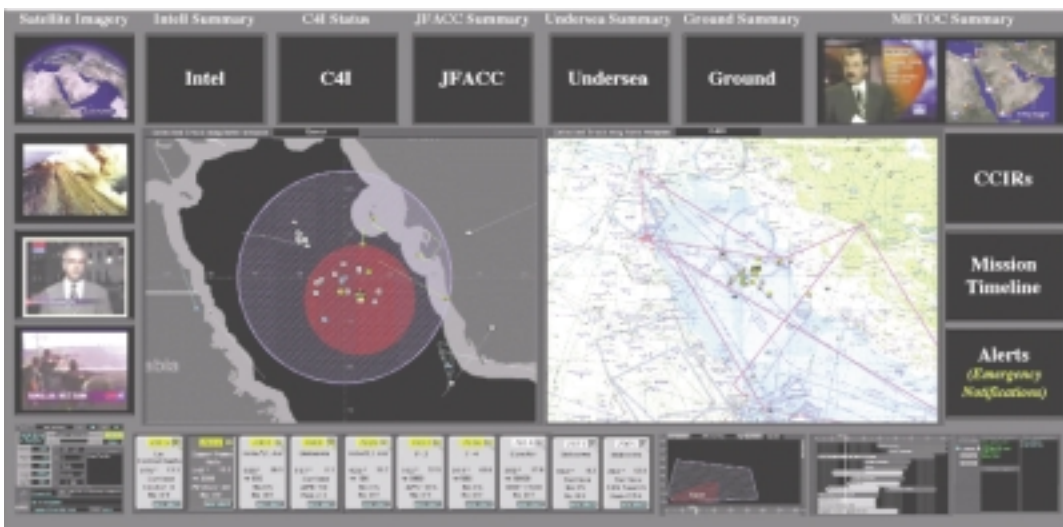
Figure 2. Command 21 Knowledge Wall vision

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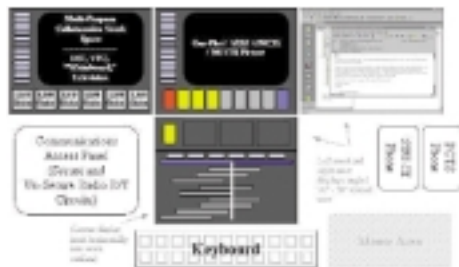
Figure 3. Conceptual Command 21 Knowledge Desk

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wargame. The objective of this game was to explore how the elimination of "stove pipe" command and control systems (i.e., "network-centric warfare") might change the way we perform military missions. The wall was designed given the COTS hardware and software capabilities that exist today so as to minimize development costs, and therefore differs from the original Command 21 Knowledge Wall vision. The knowledge wall as installed in the

Figure 4. Global 2000 Wargame Knowledge Wall

Joint Command Center at the Naval War College can be found in Figure 4.

The peripheral displays are intended to provide summary information for each of 14 functional areas of the CJTF command identified through knowledge engineering with the staffs of the U.S. Navy Third Fleet, Carrier Group One, and Carrier Group Three. Each summary display is formatted consistently by using a template-authoring tool that facilitates the creation of, and linking to, a variety of web content without the operator responsible for producing content knowing hypertext mark-up language (HTML). Additional authoring tools were provided to facilitate the creation and publishing of map-based tactical data. All pages are implemented as HTML pages on a com-

mon server, with numerous links to more detailed pages for supplemental information.

Figure 5 shows how the information might look in a representative summary display. The title line indicates the functional area described by the display. The "stop lights" in the top left quadrant are intended to be viewable from 15–20 feet away, and indicate the status of activities in various time frames. Light colors indicate the severity of the alerts in terms of their deviation from the plan. The bottom left quadrant provides space for a summary graphic or multi-media object. The right side of the screen provides space for amplifying links/headlines. "Alerts" describes specific problems within this domain/functional area that might be of interest to others. The "Impacts" links describe the impacts/issues of alerts in terms of effects to other functional areas. The "Links" area allows access to reference and supplemental
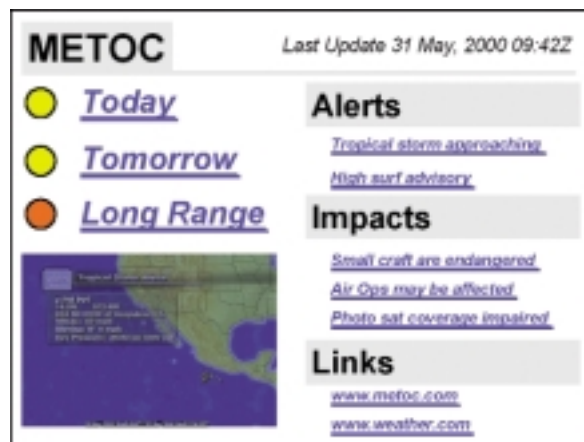
Figure 5. Representative summary display

material. Any text or graphic in the page may be linked to a more detailed Web page.

The Global 2000 wargame showed how network-centric warfare, in combination with decision support and a Web-enabled command and control architecture, can move tomorrow's military to a "knowledge-centric warfare." At the start of the game, it was argued that "speed of command" meant not having to stop to have a situation briefing to figure out what was known across the staff. Through the use of the knowledge wall and a number of information technology-based collaboration tools, not one staff briefing was required through eight days of game play. The wall was used extensively, with 30–70 unique summary pages being accessed each hour.

Both the TADMUS and Command 21 projects have empirically demonstrated how the application of decision support technology and effective human factors can improve military decision-making by turning data into meaningful information presented where, when, and the way it is needed. ■

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